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SURFACE WAVE ATTENUATION IN THE TIBETAN PLATEAU FROM AMBIENT NOISE
Annual Report

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14. ABSTRACT
In this project, we explore methodologies to extract amplitude information from the empirical Green functions (EGF) derived from ambient noise correlations and to map attenuation of surface waves. Our approaches are to combine theoretical derivations, numerical simulations, and practical considerations. A particular problem in retrieving amplitudes from noise is that the ambient seismic noise source is not uniform and changes with time. Theoretical insights show that even in the case of incompletely diffuse noise fields, we can robustly recover not just travel times, but also ray arrival amplitudes, the ambient field's specific intensity, the strength and density of its scatterers if any, and most importantly, attenuation. We propose two approaches: linear array methods and more general methods for 2D station networks. Numerical simulations show that amplitudes and attenuations can indeed be extracted from noise correlations for a linear array or for a more general 2D array. We propose a temporal flattening procedure to speed up convergence while preserving relative amplitudes. For real data, we propose an "asynchronous" temporal flattening procedure that does not require all stations to have data at the same time. Tests on real data suggest attenuations are extracted that are comparable with those from earthquakes.

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1. Summary

In this project, we explore methodologies to extract amplitude information from empirical Green functions (EGF) derived from ambient noise correlations and to map the attenuation of the surface waves. Our objectives are: (1) To develop methods for extracting attenuation from ambient noise; (2) To develop methods for practical applications using the Tibetan Plateau as a test bed; (3) To develop preliminary surface wave attenuation maps of the Tibetan Plateau. Our approaches are to combine theoretical derivations, numerical simulations, and practical considerations. A particular problem in retrieving amplitudes from noise is that seismic ambient noise source is not uniform and it changes with time. Theoretical insights show that even in the case of incompletely diffuse noise fields, we can robustly recover not just travel times, but also ray arrival amplitudes, the ambient field's specific intensity, the strength and density of its scatterers if any, and most importantly attenuation. We propose two approaches with detailed formulations: linear array methods and more general methods for 2D station networks. Our numerical simulations validate that amplitudes and attenuations can indeed be extracted from noise correlations for a linear array or for a more general 2D array. We propose a temporal flattening procedure that is effective in speeding up convergence while preserving relative amplitudes. For real data, we propose an "asynchronous" temporal flattening procedure that does not require all stations to have data at the same time. Tests on real data suggest attenuations are extracted that are comparable with those from earthquakes.

2. Introduction

This is the first year of the project. The objectives of this research are to develop methods for extracting attenuation from ambient noise, to develop methods for practical applications using the Tibetan Plateau as a test bed, and to develop preliminary surface wave attenuation maps of the Tibetan Plateau.

A particular problem in retrieving amplitudes from noise is that seismic ambient noise source is not uniform and it changes with time. Our approaches are to combine theoretical derivations, numerical simulations, and practical considerations. In this report, we show the progresses we've made on all fronts (theory, simulation, and practice). These progresses show not only the great promise of the methodologies, but also practical approaches for application to real data.

3. Methods and procedures

We have described our basic approaches previously (Weaver, 2011; Song et al., 2012). Below is a brief outline of the methodologies and procedures. A full examination of the amplitude X of a correlation waveform between stations *i* and *j* shows that it takes the form

$$X_{ij} = 2s_i s_j B_i(\hat{n}_{i\to j})\sqrt{2\pi c / (\omega_o \,|\, x_i - x_j \,|)}\ \exp(-\alpha \,|\, x_i - x_j \,|) \tag{1}$$

where $\alpha|x_i-x_j|$ is the average attenuation between stations *i* and *j*; ω_o is the frequency; c is wavespeed, and s_i and s_j are site effects at the two stations.

B_i is the ambient intensity in the direction from *i* towards *j* evaluated at station *i*. An important and useful result from this research is that the ray amplitude *X* depends only on *B* in that direction as an asymptotically valid approximation (at the next order, the differences with respect to direction are of order 1% or less).

3.1 The case of a linear array

For a linear array, along a direction $\hat{n}$ of several seismic stations, the amplitudes X_{ij} of cross correlation arrivals for j > i is

$$X_{i<j} = 2s_i s_j B_i(\hat{n}_{i\to j})\sqrt{2\pi c / (\omega_o \,|\, x_i - x_j \,|)}\ \exp(-\int_{x_i}^{x_j} \alpha\, dx). \tag{2}$$

Formulation I-1: path average. Eqn (2) indicates that amplitude X from station i (near one end of the array) to all stations j in one direction (to the other end of the array) depends only on the intensity at station i along the same strike direction. Thus the slope of the logarithm of the geometrically corrected amplitude, X.sqrt(distance), as a function of distance would give an estimate of the average attenuation (coefficient α) along the linear array.

Formulation I-2: inversion for a linear array. The system in eqn (2) can be linearized by taking the logarithm, as in traditional earthquake-based attenuation studies (e.g. Yang et al., 2004). This system is overdetermined and can be solved with a reasonable number of stations. Taking N to be the number of stations along this array, we have at most N(N-1)/2 such ray-amplitudes in one direction. Using one parameter per station to describe the local attenuation, there are up to 3N unknowns (the site factor, the B value along direction $\hat{\boldsymbol{n}}$, and one local attenuation factor at each station). Correlations from the direction $-\hat{\boldsymbol{n}}$ can provide up to N(N-1)/2 additional amplitudes and N additional unknowns B. Thus if amplitudes along both directions are available, one needs only 5 to 7 stations along this line to solve for all the unknowns. This is a very general approach without *a priori* constraints on the noise intensity.

Formulation I-3: assuming no internal scattering. The noise intensity cannot be arbitrary. If we assume the ambient noise sources are from the far field (many studies have pointed to the oceans for the seismic bands we are interested in) and further assume that scattering is not important, it can be shown that the noise intensity B decays like exp(-2.α.distance), where is α the same medium attenuation coefficient we are trying to extract. Thus in this formulation, we need only two Bs (one at each end of the linear array).

3.2 The case of a 2D station network

Formulation II-1: an expansion of the linear array approach. In general, we have a network of stations whose distribution is irregular throughout the study region. However, we may be able to identify 3 or more stations that roughly lie on the same great circle path. In this case, we can use amplitude ratios to eliminate the unknown intensity B along that direction. Similar ideas are commonly used in earthquake studies to measure phase velocity between two stations (the "two-station" method) or derive surface attenuation using amplitude ratios between two stations aligned along the great circle with an earthquake (e.g. Yang et al., 2004).

Consider 3 stations (station 1, 2, 3) on the same great circle, the ratios of the *geometrically-corrected* amplitudes is $X_{13}/X_{12}=s_3/s_2 \exp(-\alpha_2 x_2)$, $X_{31}/X_{32}= s_1/s_2 \exp(-\alpha_1 x_1)$, where s_i is the site factor for station i, x_1 and x_2 are distance between stations 1 and 2 and stations 2 and 3, respectively, and α_1 and α_2 are average attenuation coefficients between stations 1 and 2 and stations 2 and 3. If we assume no internal scattering, such that intensity B decays like exp(-2α.distance) as discussed above, we can use two other amplitude ratios: $X_{23}/X_{12}=s_3/s_1 \exp(-\alpha_1 x_1-\alpha_2 x_2)$, and $X_{21}/X_{32}=s_1/s_3 \exp(-\alpha_1 x_1-\alpha_2 x_2)$. The logarithm of such an amplitude ratio is linear with distance. Once enough amplitude ratios are measured along paths of different azimuths and locations to provide sufficient coverage, it is straightforward to discretize the region and construct a tomographic inversion for the attenuation coefficients for the entire region.

Formulation II-2: the most general approach. The linear array approach relies on identifying a linear array of sufficient length. How might one use sets of seismic stations that are not aligned along a linear array? How quickly ought one permit the diffuse intensity B implicit in the above formulation to vary in direction and from place to place? The diffuse intensity B, in particular how it is permitted to vary in space and direction, cannot be arbitrary. The noise field ought to obey a Radiative Transfer Equation (RTE) (e.g., Turner and Weaver 1994), which involves noise intensity, noise sources, scattering strength, and attenuation. In this project, we will explore this situation in theory and in practice.

4. Results

4.1. Numerical simulations: Tests on linear arrays

We reported previously that attenuation can be extracted along a linear array using simulated data with an azimuthally varying noise source (Weaver, 2011; Song et al., 2012). The simulations included a simple case of a uniformly spaced linear array of receivers, homogeneous attenuation and wave speed and mild directionality to the noise field. Numerical simulations have now been extended to a broader class of systems, with spatially varying attenuation, highly directional noise intensities, and irregular line arrays. This is described in detail in Weaver (2013). However, the random noise sources do not change in time. For these simulations, it is shown that accurate attenuations and site factors can be retrieved. Furthermore, errors in attenuation measurements can also be determined (Fig. 1).

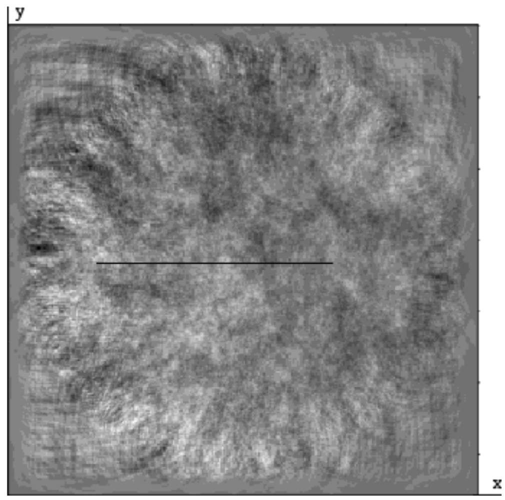

Fig. 1. Simulation 'A'. Snapshot of the broad-band wavefield in a 271 × 271 array, which seismically scales to 800 km, before bandpass filtering. *The strong absorption on the edges and anisotropic annulus of sources are evident. The horizontal line indicates the line along which six stations were uniformly placed in the simulation. Other simulations had irregular station spacings and a longer line array extending a bit further to the right. (Weaver, 2013)*

(a) (b)

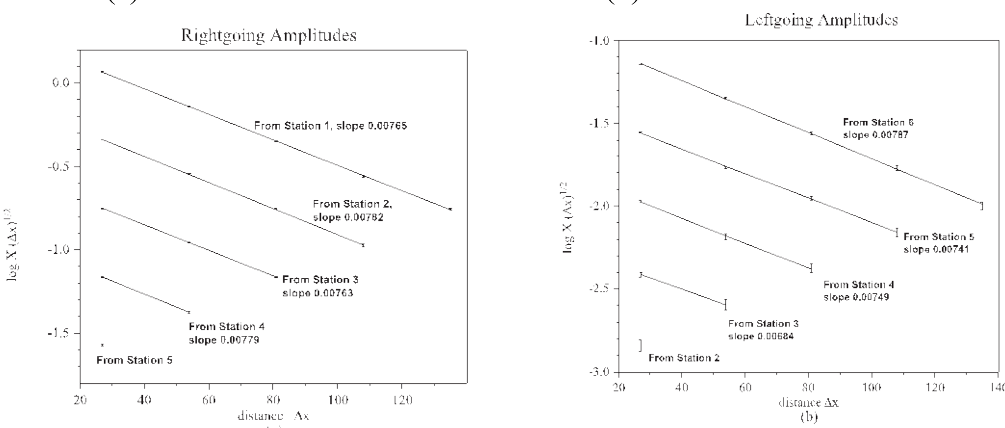

Fig. 2. (a) The amplitudes X of the arrival wave packets in the rightgoing correlation waveforms from simulation 'A' are plotted versus interstation distance. *One-sigma error bars are taken from the last column of the table, δlogX = δX/X. Amplitudes corresponding to the same pseudo-source fit well to straight lines. The observed slopes correspond well to the expected 0.00777 nepers per mesh spacing. (b) The leftgoing amplitudes in simulation 'A' have larger error bars, corresponding to the relatively weaker ambient noise intensity coming from the right.*

4.2 Numerical simulations: "Earth-like" temporally variable noise field

1) A 1D array case

To examine our ability to extract attenuation from ambient noise methods, we impose Earth-like temporally variable noise intensity on simulated diffuse fields. The setup for our simulation is shown in Fig. 3. The source intensity includes smoothly varying intensity as well as a strong "local" intensity (as indicated from the shade on the source "ring"). The study region is divided into four parts inside the source "ring". 10 receiver stations with a spacing distance of 85 km were arranged in a linear array, where 5 receiver stations are in the lower left region and the other 5 receiver stations are located in the upper right region. An attenuation model with two different attenuation coefficients, $\alpha_1 = 0.00259$ in the lower left region and $\alpha_2 = 0.00388$ in the upper right region, was used. The site responses of all stations in the experiment are set to 1.

We add the seismic data from a station in the USArray into our simulation data to simulate the natural seismic noise. The seismic noise is from a 4-year continuous seismic waveform after clipping earthquakes and spikes. We then multiply this seismic noise with the synthetic noise field point by point to generate the synthetic noise field with temporally varying strength. We call the original simulation data "original" data and the data with seismic noise "raw" data in our discussion below. The sample rate of the data is 3 points per second, and a total of about 1 year of data are generated at each station.

In order to retain rapid convergence amidst time-varying noise intensity, we use a "temporal flattening" procedure that we proposed earlier (Weaver, 2013; Song et al., 2012). Each station's band-limited signal is normalized by a running average of the *total* band-limited array energy. Thus each station is treated equally, and relative amplitudes are preserved.

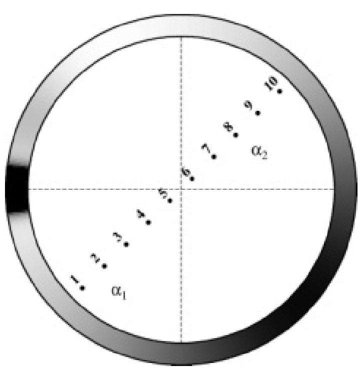

Fig. 3. Simulation 'B'. (A) Distribution of source intensity and receiver locations. *The Gaussian noise source is highly non-uniform as indicated by the shades along the circumference. We have also added temporal variation of the noise source, which mimics temporal variation of a seismic station on Earth. The attenuation inputs include four different values at the four quadrants.*

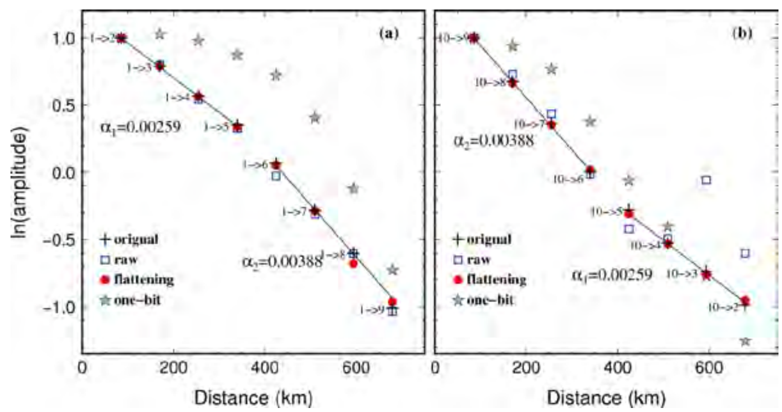

Fig. 4. Amplitudes extracted from Green's Functions with different pre-processing procedures for Simulation 'B'. *The lines are true values from the inputs. (a) from Station 1 to other stations. (b) from Station 10 to other stations.*

The results are shown in Fig. 4. We see that the amplitude decays of the "raw" data are similar to that of the "original". But when the signal to noise ratios of the Green's Functions is low (Fig. 4b), the amplitudes are not stable. The amplitudes from the one-bit processing are apparently not correct; the behavior is not linear. The amplitude decays from the flattening procedure are very close to the true values.

2) A 2D array case

The set up for this simulation (Simulation 'C') is the same as above, but the wavefield is recorded at a 2D array (10x10 or a total of 100 stations with uniform spacing). The input attenuation of the medium is not uniform: it has four different values at the four quadrants of the array. Following Formulation II-1, we identify linear arrays within an azimuth of 10 degrees for each station. We then form amplitude ratios for stations along each linear array. We obtain a total of about 5600 independent amplitude ratios. These amplitude ratios are then used to invert for 2D attenuation maps and site factors. The inversion with 4 cells (as in the input model) recovers perfectly the input model and the inversion with 36 cells recovers quite well the input model except cells at the corners which are not constrained by the amplitude ratios (Fig. 5).

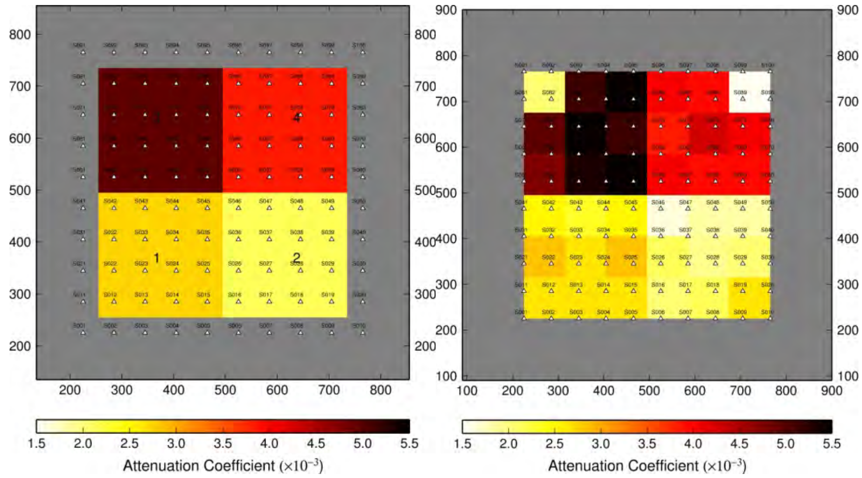

Fig. 5. Extraction of attenuation from 2D array with simulated data (Simulation 'C'). *The input model has four different values at the four quadrants, respectively. The noise source varies in strength azimuthally. (A) The input Qs are fully recovered using a 4-cell parameterization. (B) The input Qs are reasonably recovered in a 36-cell inversion, except at the four corners, which are not constrained by the method.*

4.3. Tests on real data

We have conducted various tests on amplitude extracted from real data. Here we show some test results using stations in the western U.S. (Fig. 6). We dealt with a number of practical issues, including energetic arrivals, not all stations have signals, and energetic arrivals may appear at different times for different stations (Fig. 7), by a new proposed "asynchronous" temporal flattening (ATF) procedure (Fig. 8); this led to an issue of window length for the flattening procedure (Fig. 9). The amplitude attenuations extracted from the ambient noise seem compatible with those from earthquakes (Fig. 10).

Because not all stations have signals and energetic arrivals may appear at different times for different stations, if we require all stations have the exactly the same overlapping time segments, we will discard a lot of data, making the convergence of the Green's Functions difficult. To address this issue, we proposed a new "asynchronous" temporal flattening (ATF) procedure, as follows.

1) Window out energetic signals for each individual trace. Keep track of points that are kept and points that are windowed out.
2) Select a window length for ATF.
3) Calculate the RMS amplitude of ALL traces for that time window. Only points that have been kept after windowing are used.
4) Divide each trace within the time window by the RMS.

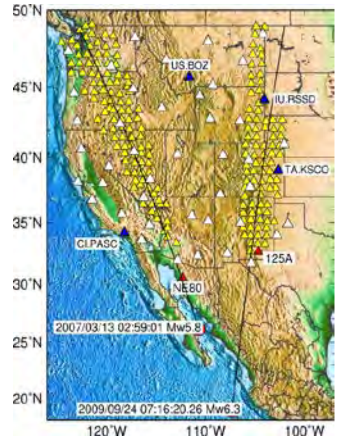

Fig. 6. Map of stations in the western U.S. used in our tests. *Indicated also are two earthquakes used to compare with ambient noise results.*

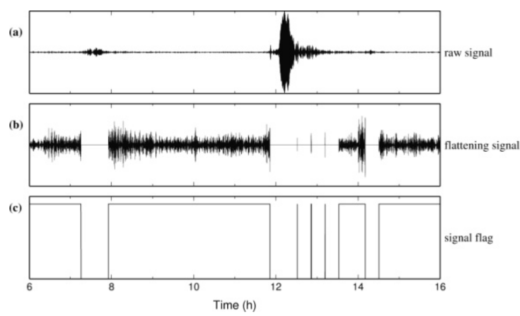

Fig. 7. Data preprocessing. *For a given trace, energetic signals are first windowed out. A flag trace is constructed to keep track of points that are kept (values of 1) or windowed out (values of 0). The windowed trace is then "flattened" using the average root-mean-square amplitude over a period of time (e.g. hours) using all stations and data points that have not been windowed out.*

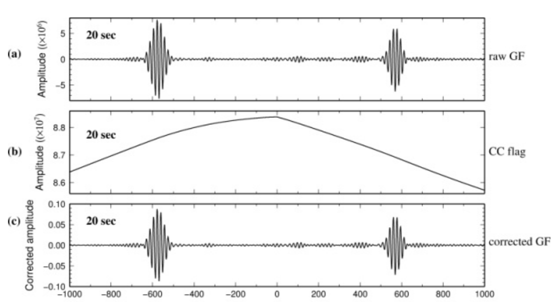

Fig. 8. (A) A raw empirical Greens function (EGF) is constructed from the cross-correlation of "flattened" traces. (B) Cross-correlation is constructed using the flag traces, which indicates the number of data points that have been used in the EGF for a given time lapse. (C) The raw EGF is normalized by the number of data points in the flag CC to yield the normalized EGF.

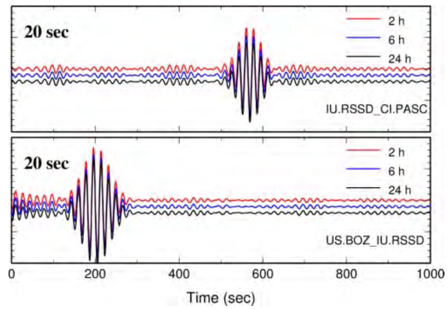

Fig. 9. Tests on the windows used in the temporal flattening procedure. *Shown are results for window length of 2 hours to 24 hours. The traces and amplitudes are identical and thus our window length in the flattening procedure can be quite wide (1 day).*

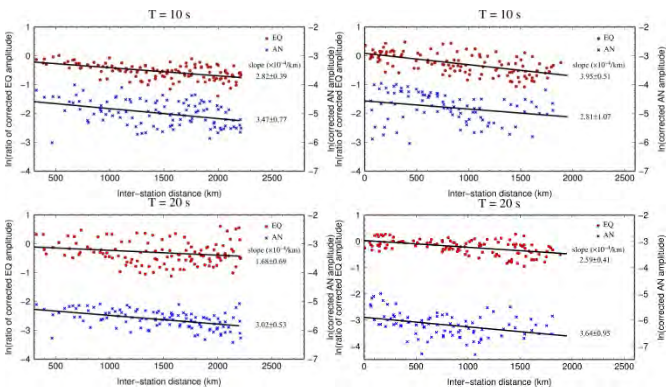

Fig. 10. Comparison of amplitude decays obtained from earthquakes (red dots) and ambient noise (blue crosses) at two periods (10 and 20 s). *Left two panels are for the western group of stations and the event in 2007 (Fig. 4) and right panels are for the eastern group of stations and the event in 2009. Approximately 18 months of ambient noise data are used in calculating the EGFs.*

5. Conclusions

1) Based on theoretical considerations, we formulated several approaches for extraction of amplitudes from ambient noise. The formulations take into account non-uniform and anisotropic source and internal scattering.
2) Numerical simulations validate that amplitudes and attenuations can indeed be extracted from noise correlations for a linear array or for a more general 2D array.
3) We propose a temporal flattening procedure that is effective in speeding up convergence while preserving relative amplitudes. For real data, we propose an "asynchronous" temporal flattening procedure that does not require all stations to have data at the same time. The flattening procedure can have a long window length (1 day).
4) Tests on real data extract attenuations that are comparable with those from earthquakes.

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